CTEQ Studies of Parton Distribution Functions in the Transition and DIS Regimes

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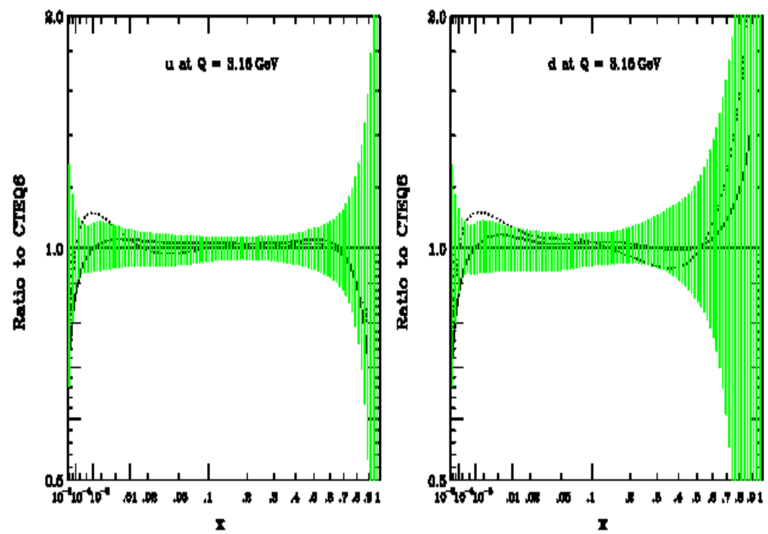
Fermilab

CTEQ
What are we doing relevant to ν-A scattering?

- CTEQ (Coordinated Theoretical-Experimental Project on QCD) grew out of joint work Wu-Ki Tung and I performed to produce the Morfín-Tung Parton Distribution Functions (PDFs) in 1989/90.
- CTEQ, now a collaboration of 23 theorists and 10 experimentalists, has the goal of studying both perturbative and non-perturbative QCD, organizing workshops and a yearly school on QCD Analysis and Phenomenology and global fits of data to yield PDFs.
- Three main areas of study:
  - High W/Q^2 Nucleon PDFs incorporating the latest LHC results (CT10/12 PDFs)
  - Study of the lower-W/higher-x region, covering transition and low-Q DIS (CTEQ - Jefferson Lab collaboration)
  - Nuclear PDFs
- I'll concentrate on the last two areas in this very short review.

Higher-x, lower-W PDFs
CTEQ-Jefferson Lab Collaboration

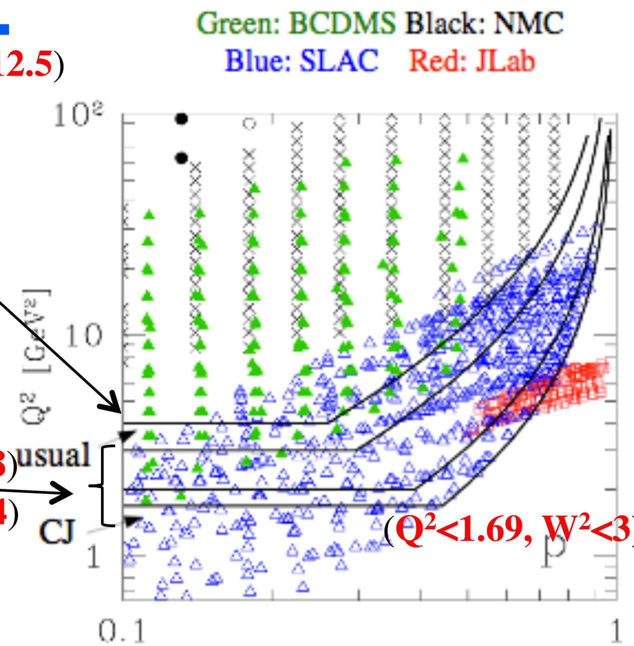
- Collaboration: A. Accardi, E. Christy, C. Keppel, W. Melnitchouk, P. Monaghan, J. Owens
- Goals
  - Global QCD fits of PDFs **focused on large-x d & u valence quarks**.
  - Improve the PDF experimental precision ("PDF errors"): increase the fitted data set
  - Include all relevant large-x / small-Q^2 theory corrections.
  - Quantitatively evaluate theoretical systematic errors.



- Include Target Mass Corrections (TMC) and Higher Twists (HT)

CTEQ-Jlab Results – E. Christy Presentation

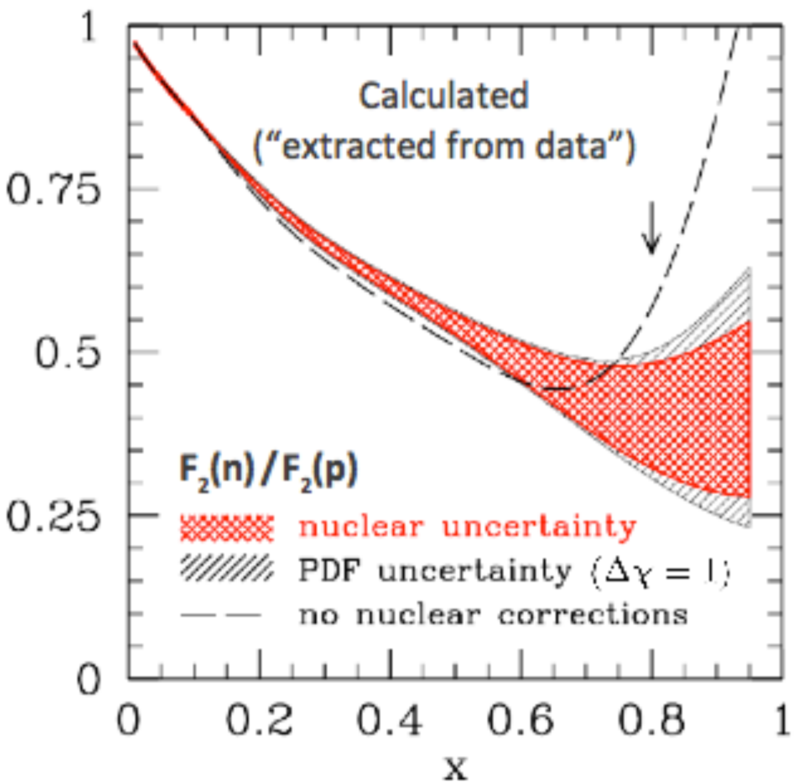
- When using the Standard CTEQ cuts ($Q^2<4$, $W^2<12.5$)
  - The fitted PDFs are (relatively) insensitive to TMC and HT.
  - Nuclear (deuterium) corrections are not negligible (but usually neglected...)
- Looser kinematic cuts ($Q^2<3$, $W^2<8$) ($Q^2<2$, $W^2<4$)
  - PDFs stable as kinematic cuts are varied
  - Substantial reduction in "experimental" PDF errors

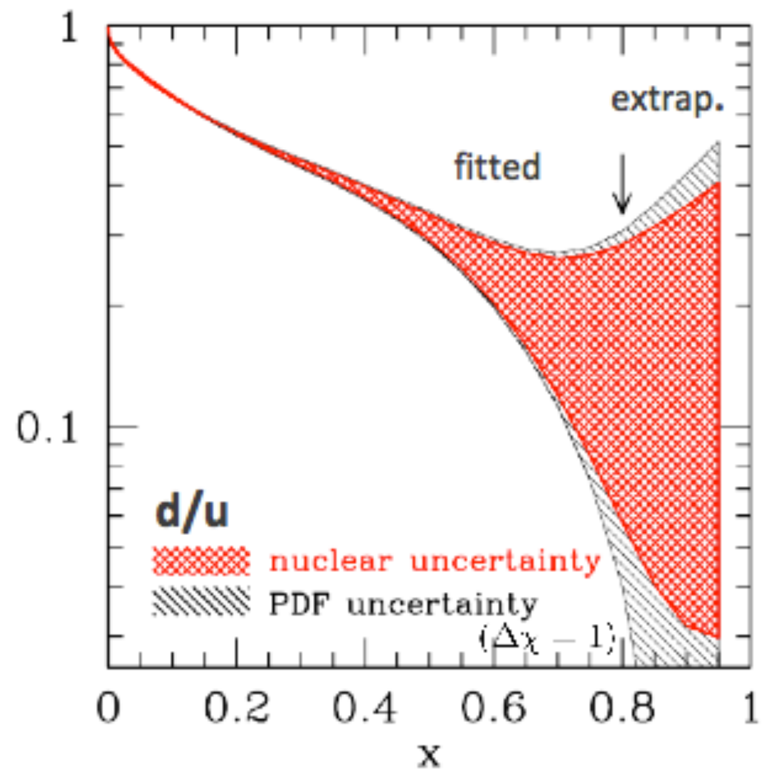


- Intriguing stability with respect to Target Mass Corrections
  - The fitted HT term compensates for differences in TMC models
  - Leading-twist PDFs have little systematic error (good!)
  - HT term has ≈ 50% uncertainty (not so good, if you care for this...)
- New *d*-quark parameterization requires deuterium data!
  - **Large** sensitivity to nuclear model for deuterium!

The CTEQ-JLab $F_2(n)$ / F_2 (p) and d/u

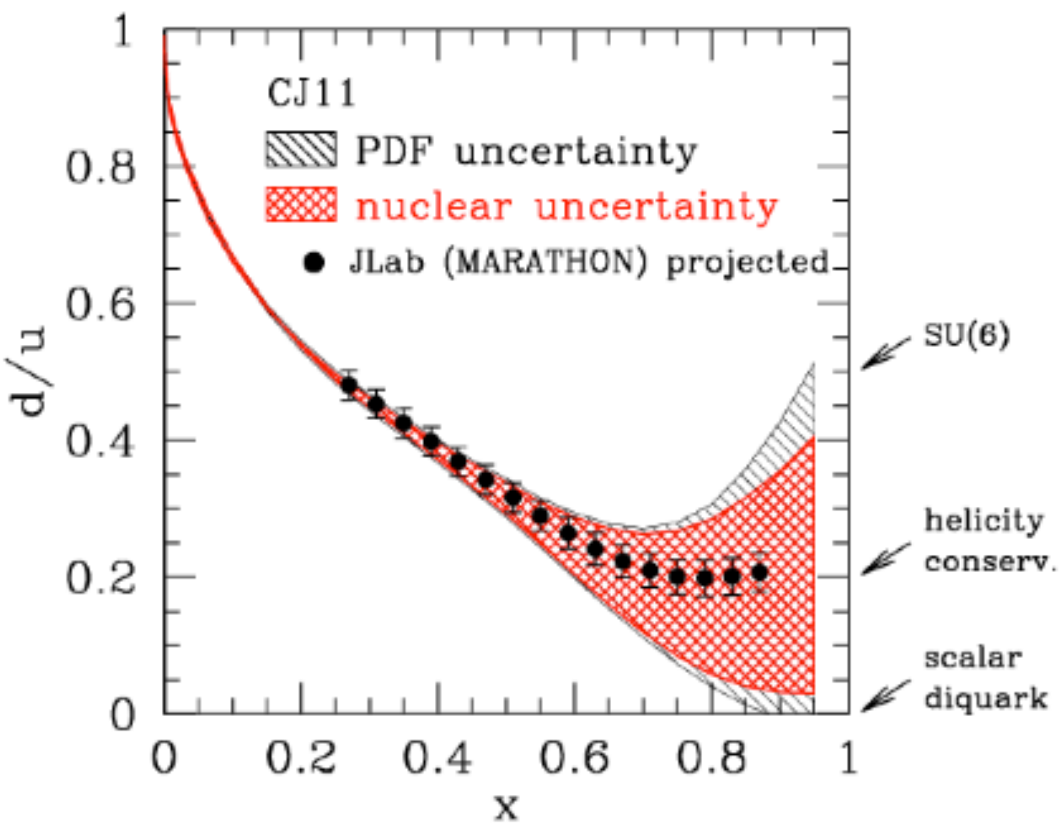
- Well behaved extrapolation for each nuclear model
- But: **large nuclear uncertainty (covers all theory predictions)**
  - Nuclear uncertainty **totally masks improved statistics** from low-W^2 data

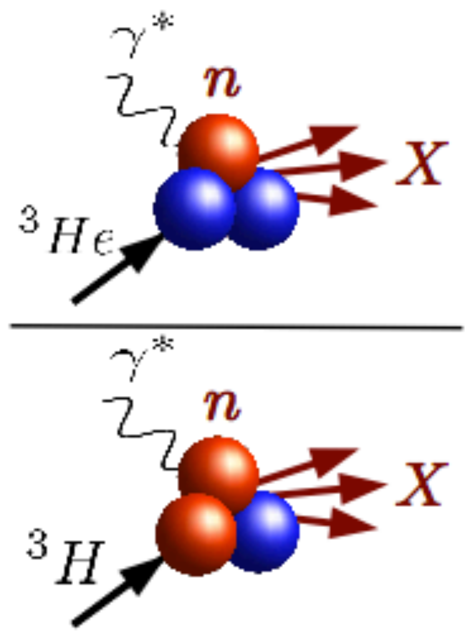




We need more experimental data!
BONUS and MARATHON

- BONUS described by E. Christy.
- Quasi-free neutrons from MARATHON.
    - approved Jlab12 experiment.
- Nuclear corrections largely cancel in ratio of 3He/3H cross sections.





High-x Structure Functions & PDFs

ν - p Scattering

$$\left.\begin{aligned} F_2^{\nu p} &= 2x\,(d + \bar{u} + s) \\ F_2^{\bar{\nu} p} &= 2x\,(\bar{d} + u + \bar{s}) \end{aligned}\right\} \xrightarrow{\text{At high } x} \boxed{\frac{F_2^{\nu p}}{F_2^{\bar{\nu} p}} \approx \frac{d}{u}}$$

Add in…

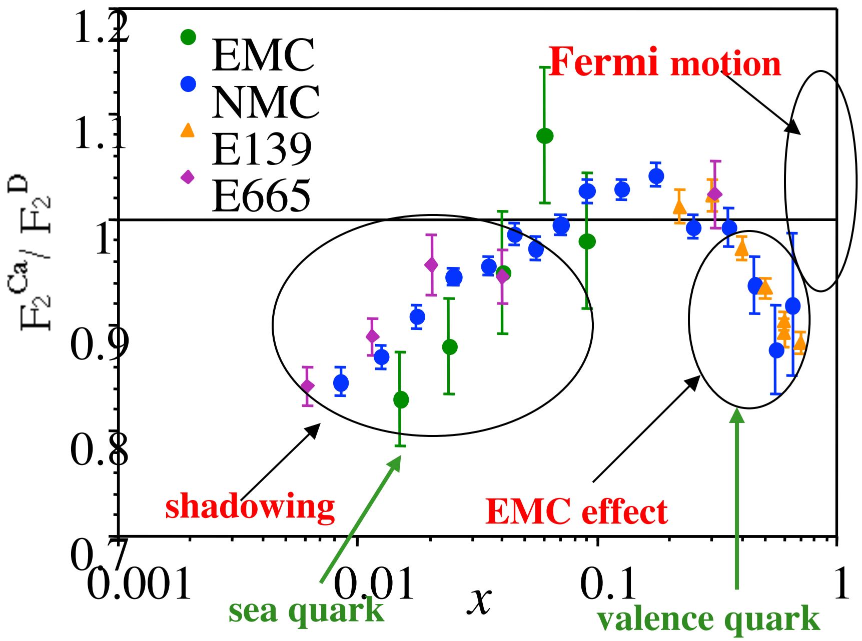
$$\left.\begin{aligned} xF_3^{\nu p} &= 2x\,(d - \bar{u} + s) \\ xF_3^{\bar{\nu} p} &= 2x\,(-\bar{d} + u - \bar{s}) \end{aligned}\right\} \longrightarrow \begin{aligned} F_2^{\nu p} - xF_3^{\nu p} &= 4x\bar{u} \\ F_2^{\bar{\nu} p} + xF_3^{\bar{\nu} p} &= 4xu \end{aligned}$$

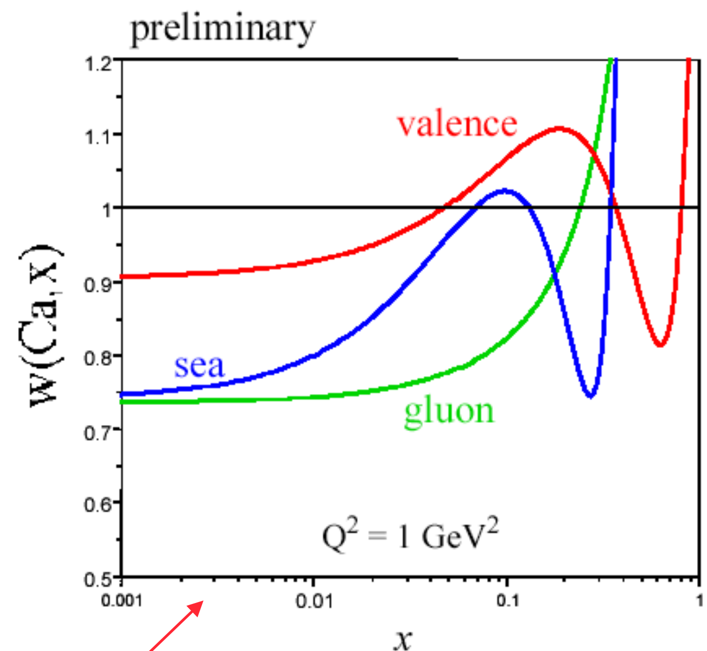
MINERνA future Run with H_2 in the Cryo-target and NuMI HE beam?

Speaking of Nuclear Effects in Neutrino Interactions

- Target nucleon in motion - spectral functions (Benhar et al.)
- Certain reactions prohibited - Pauli suppression
- Quasi-elastic form factors are modified within the nuclear environment. (Butkevich / Kulagin, Tsushima et al.)
- Meson exchange currents: multi-nucleon initial states
- Produced topologies are modified by final-state interactions modifying topologies and reducing detected energy.
  - Convolution of $\delta\sigma(n\pi)$ x formation zone uncertainties x π-absorption uncertainties yield larger oscillation-parameter systematics
- **Cross sections and structure functions are modified and parton distribution functions within a nucleus are different than in an isolated nucleon. Observations from an on-going CTEQ analysis.**

Experimental Studies of (Parton-level) Nuclear Effects with Neutrinos: until recently - essentially NON-EXISTENT





- F_2 / nucleon changes as a function of A. Specifically measured in μ/e - A **not in ν − A**
- **Good reason to consider nuclear effects are DIFFERENT in ν - A**.
  - **Presence of axial-vector current.**
  - **SPECULATION: Stronger shadowing for ν -A but somewhat weaker "EMC" effect.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**

Addressing the lack of F_2^{ν} Nuclear Effects Analyses

Nuclear PDFs from neutrino deep inelastic scattering

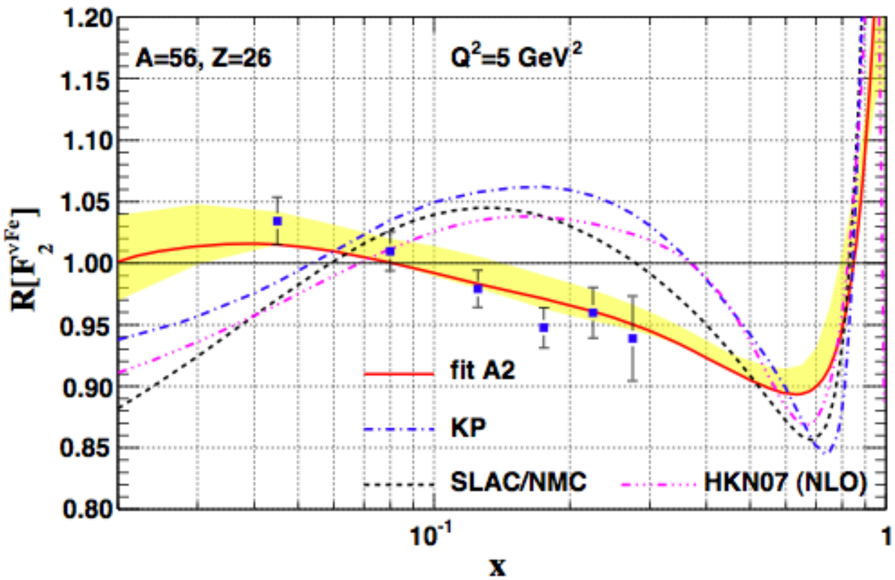
nCTEQ
K. Kovarik (Karlsruhe) I. Schienbein (LPSC-Grenoble),
J-Y. Yu (SMU), C. Keppel (Hampton/JeffersonLab)
J.G.M. (Fermilab), F. Olness (SMU), J.F. Owens (Florida State U)

Also analyses by:
K. Eskola, V. Kolhinen and C. Salgado
and
D. de Florian, R. Sassot, P. Zurita and M. Stratmann

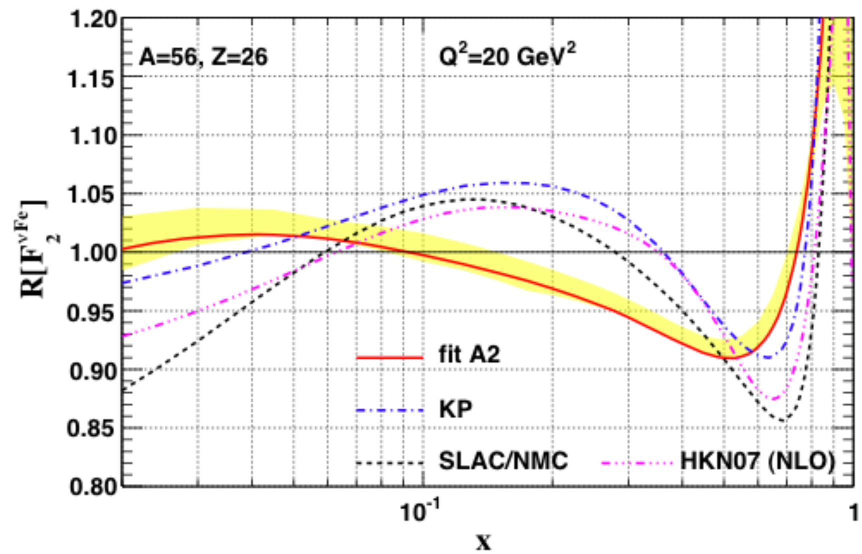
CTEQ High-x Study: nuclear effects ratio A/D_2
No high-statistics D_2 data – "make it" from PDFs

- Form reference fit mainly nucleon (as opposed to nuclear) scattering results:
  - BCDMS results for F_2^p and F_2^d
  - NMC results for F_2^p and F_2d/F_2^p
  - H1 and ZEUS results for F_2^p
  - CDF and DØ result for inclusive jet production
  - CDF results for the W lepton asymmetry
  - E-866 results for the ratio of lepton pair cross sections for pd and pp interactions
  - E-605 results for dimuon production in pN interactions.
- Correct for deuteron nuclear effects

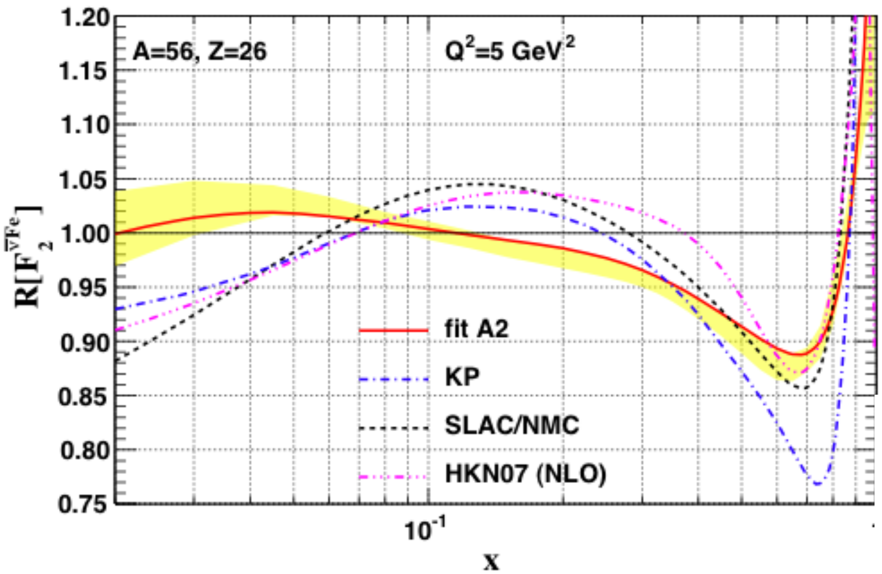
F_2 Structure Function Ratios: ν-Iron



$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$



F_2 Structure Function Ratios: $\overline{\nu}$-Iron



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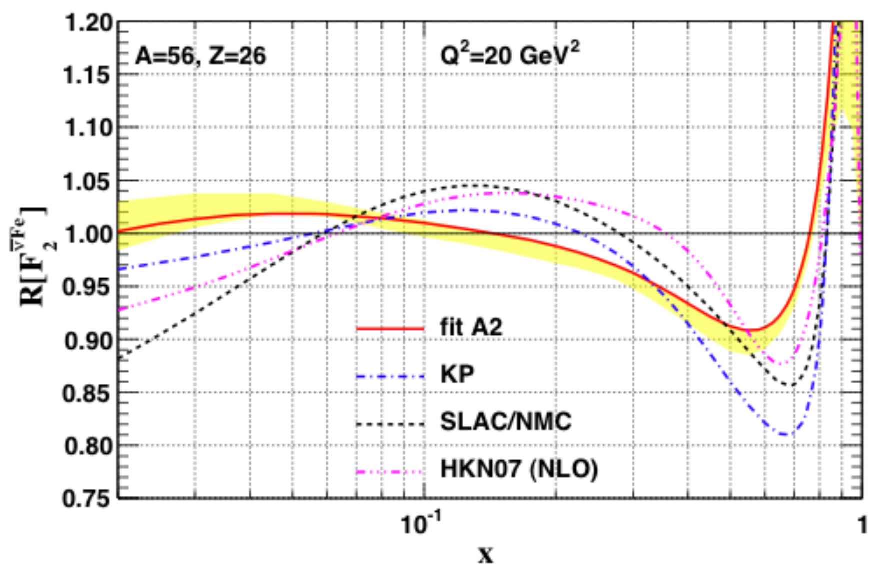
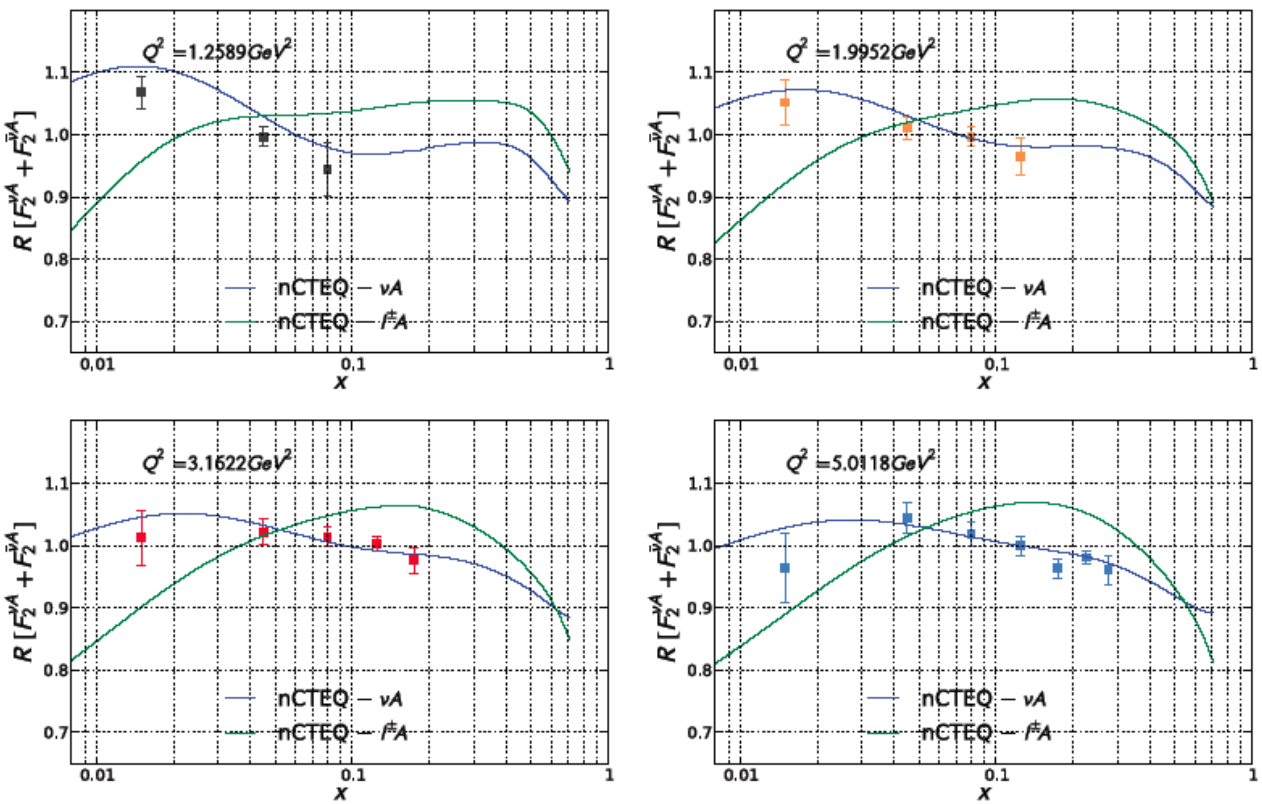


A More-Detailed Look at Differences

- NLO QCD calculation of $\dfrac{F_2^{\nu A} + F_2^{\bar{\nu} A}}{2}$ in the ACOT-VFN scheme
  - charge lepton fit undershoots low-x data & overshoots mid-x data
  - low-Q^2 and low-x data cause tension with the shadowing observed in charged lepton data



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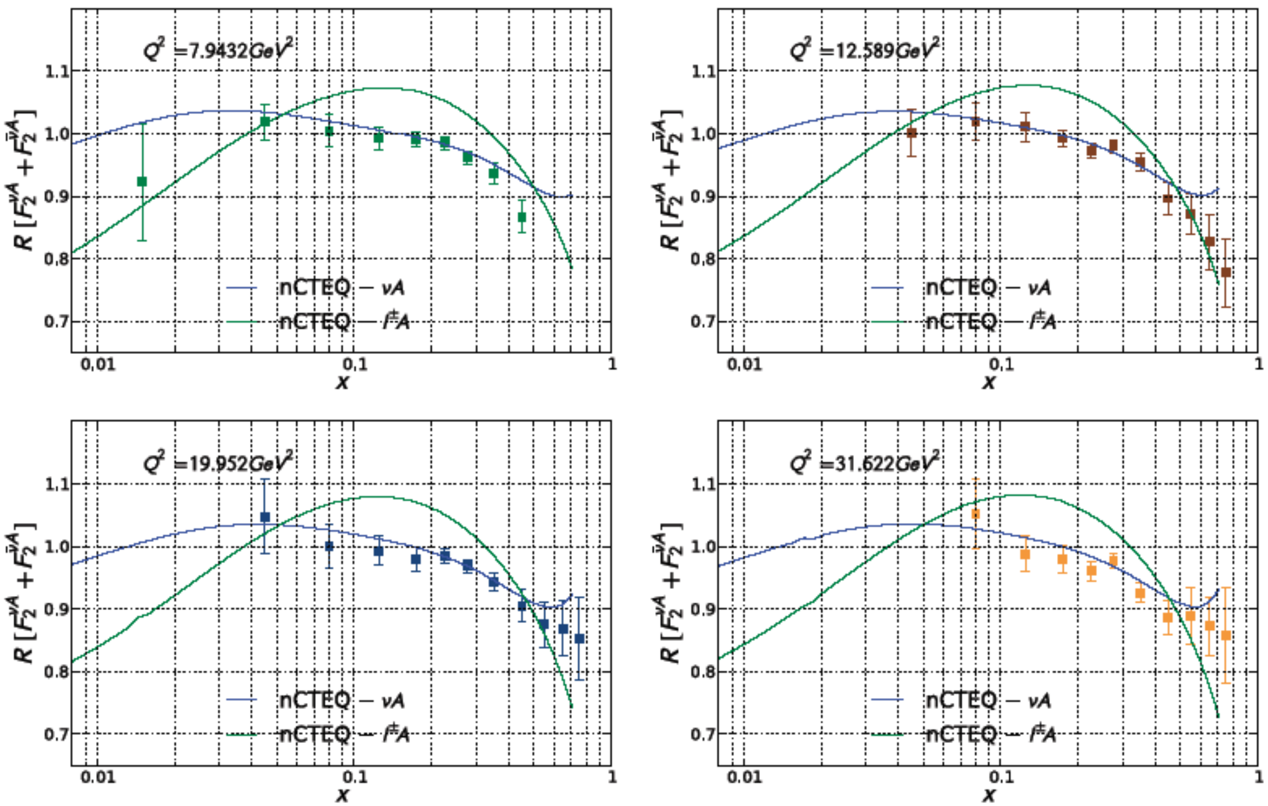


Combined Analysis of ν A, ℓA and DY data

Kovarik, Yu, Keppel, Morfín, Olness, Owens, **Schienbein**, Stavreva

- Take an earlier analysis of $\ell^{\pm}$A data sets (built in A-dependence)
  - Schienbein, Yu, Kovarik, Keppel, Morfin, Olness, Owens,
  - PRD80 (2009) 094004
- For $\ell^{\pm}$A take $F_2(A)/F_2(D)$ and $F_2(A)/F_2(A')$ and DY $\sigma(pA)/\sigma(pA')$
  - 708 Data points with Q > 2 and W > 3.5
- Use **8 Neutrino data sets**
  - NuTeV cross section data: ν *Fe*, $\overline{\nu}$ *Fe*
  - NuTeV dimuon off Fe data
  - CHORUS cross section data: ν *Pb*, $\overline{\nu}$ *Pb*
  - CCF*R* dimuon off Fe data
- Initial problem, with standard CTEQ cuts of Q > 2 and W > 3.5 **neutrino data points (3134) far outnumber $\ell^{\pm}$A (708)**.

Try to Find a Simultaneous Fit to Both $\ell^{\pm}$ and ν

Quantitative χ^2 Analysis of a Combined Fit

- Up to now we are giving a qualitative analysis. Consider next quantitative criterion based on χ^2
- Introduce "tolerance" (T). Condition for compatibility of two fits:

The 2nd fit χ^2 should be within the 90% C.L. region of the first fit χ^2

- Charged: 638.9 ± 45.6 (best fit to charged lepton and DY data)
- Neutrino: 4192 ± 138 (best fit to only neutrino data)

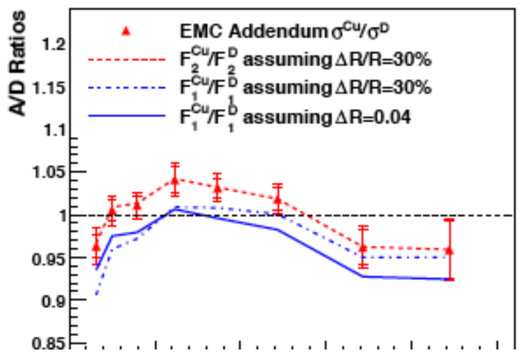
Weight	Fit name	ℓ data	χ^2	ν data	χ^2	total χ^2 (/pt)
$w = 0$	decut3	708	639	-	nnnn **NO**	639 (0.90)
$w = 1/7$	glofac1a	708	645 **YES**	3134	4710 **NO**	5355 (1.39)
$w = 1/4$	glofac1c	708	654 **YES**	3134	4501 **NO**	5155 (1.34)
$w = 1/2$	**glofac1b**	708	680 **YES**	3134	4405 **NO*** **	5085 (1.32)
$w = 1$	global2b	708	736 **NO**	3134	4277 **YES**	5014 (1.30)
$w = \infty$	nuanua1	-	nnn **NO**	3134	4192	4192 (1.33)

Others Do NOT Find this Difference between $\ell^{\pm}$ and ν

- The analyses of K. Eskola et al. and D. de Florian et al. do not find this difference between $\ell^{\pm}$–A and ν–A scattering.
- They do not use the full covariant error matrix rather adding statistical and systematic errors in quadrature.
- They do not use the full double differential cross section rather they use the extracted structure functions which involve assumptions:
  - Assume a value for $\Delta x F_3$ $(= F_3^{\nu} - F_3^{\nu})$ from theory.
  - Assume a value for $R = F_L / F_T$.
- If nCTEQ makes these same assumptions, than a combined solution of $\ell^{\pm}$–A and ν–A scattering can be found.

If Difference between both /$^{\pm}$-A and ν–A persists?

- In neutrino scattering, low-Q^2 is dominated by the (PCAC) part of the axial-vector contribution of the longitudinal structure function F_L.
- Shadowing is led by F_T and the shadowing of F_L lags at lower x.



V. Guzey et al. arXiv 1207.013

  - F_1 (Blue) is purely transverse and F_2 (Red) is a sum of F_T (F_1) and F_L
- This could be a contributing factor to such a difference.
- Another idea also from Guzey and colleagues is the observation that (in leading order):

$$\frac{d\sigma^{\nu A}}{dx dy} = \frac{G_F^2 M_W^4}{(Q^2+M_W^2)^2}\frac{ME}{\pi}2x\left[d^A + s^A + (1-y)^2(\bar{u}^A + \bar{c}^A)\right]$$

$$\frac{d\sigma^{\bar{\nu} A}}{dx dy} = \frac{G_F^2 M_W^4}{(Q^2+M_W^2)^2}\frac{ME}{\pi}2x\left[\bar{d}^A + \bar{s}^A + (1-y)^2(u^A + c^A)\right]$$

  - In the shadowing region at low-x, y is large and the σ_ν are primarily probing the d- and s-quarks. If shadowing of the d and/or s quark negligible could contribute to the result.

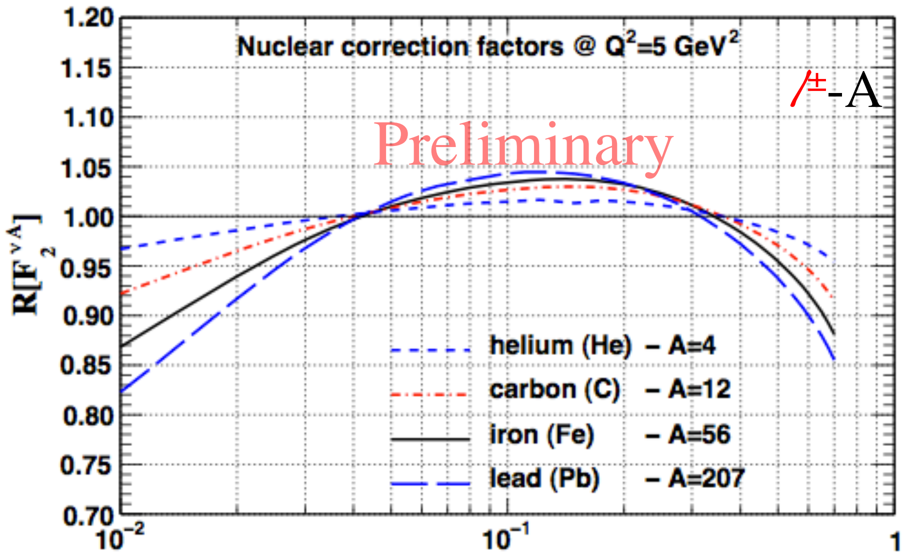
Summary and Conclusions

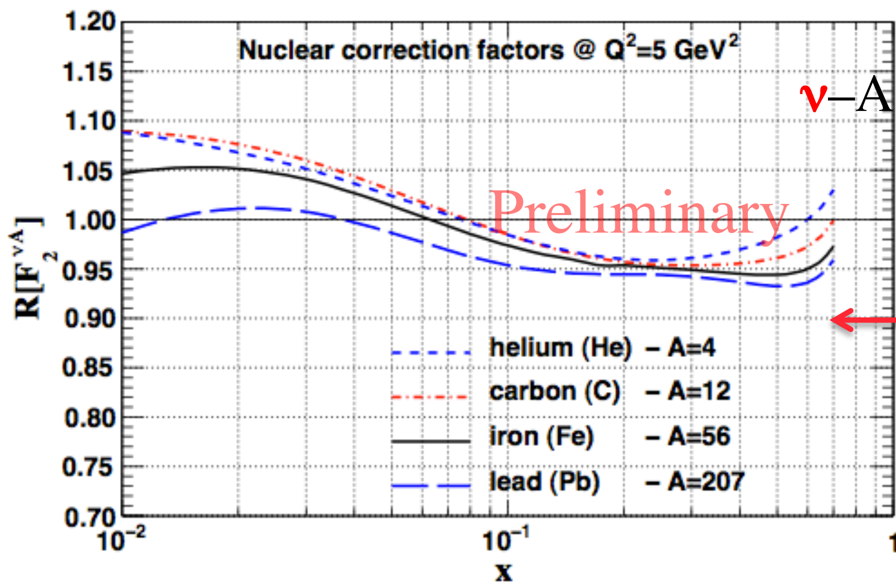
- CTEQ-Jlab studies of high-x PDFs hampered by large uncertainty in nuclear theory of deuterium – larger d-quark as x → 1 favored.
- nCTEQ finds indications from **one** experiment using **one** nucleus that **ν-induced parton-level nuclear effects are different** than $\ell^{\pm}$-nuclear effects.
  - Based on nuclear corrections factors R and the tolerance criterion, there is no good compromise fit to the $\ell^{\pm}$A + DY + νA data.
- If these differences between $\ell^{\pm}-$A and $\nu-$A scattering persist in shadowing region, the difference may (partially?) be due to the large contribution of F_L at low Q^2 in $\nu-$A scattering and/or shadowing of the strange quark.
- Need systematic **experimental** study of **ν-induced nuclear effects in A and D_2 such as MINERνA in the ME Beam.**

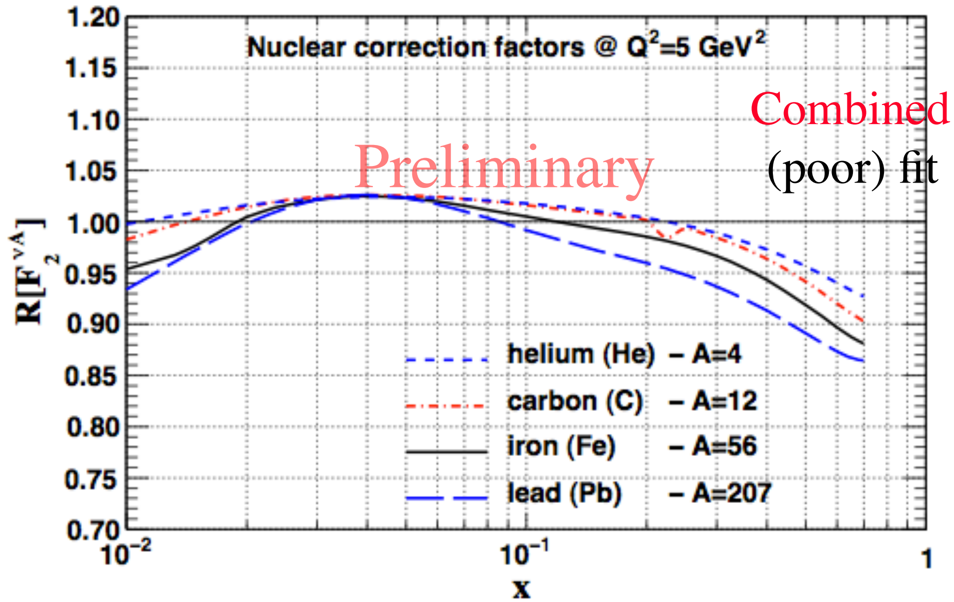
Additional Details

What could MINERνA Contribute?

Preliminary Predictions for MINERνA Targets







Careful! Based on analysis of NuTeV ν-Fe results and scaled in A **as charged lepton nucleus** scattering results!

(Karol Kovarik – Katlsruhe)

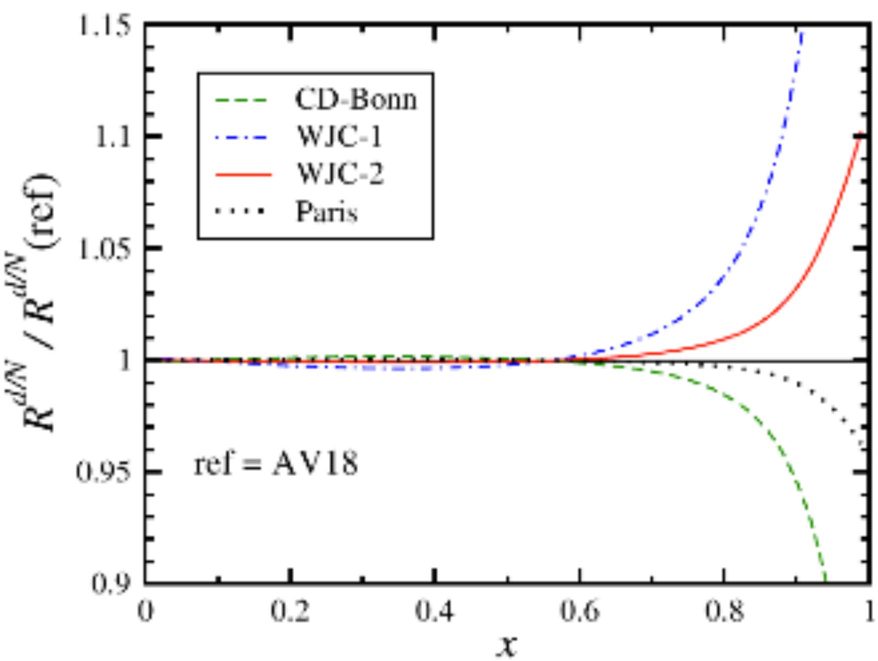
Nuclear corrections – theoretical uncertainty

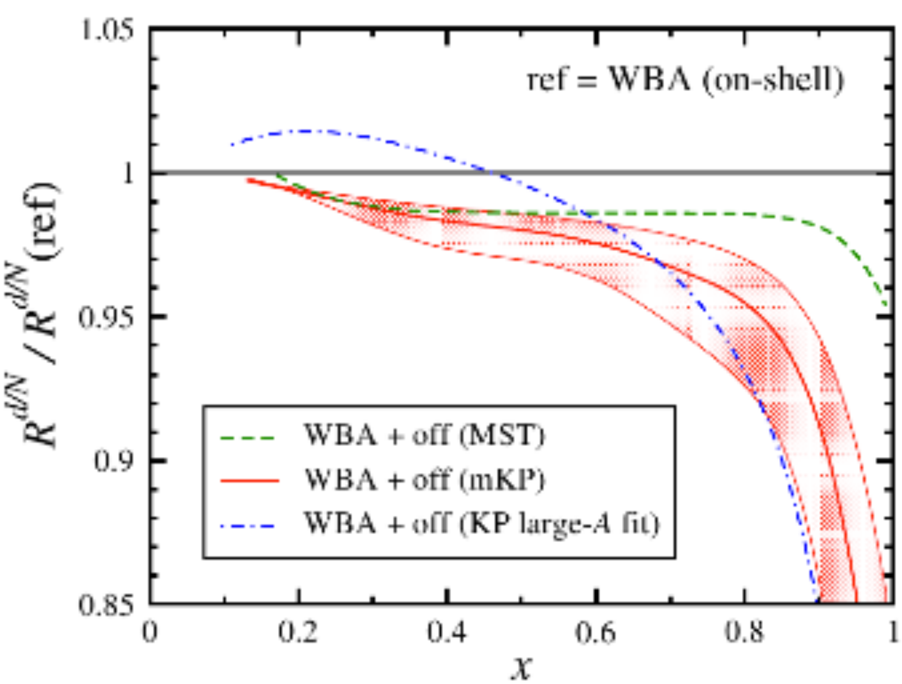
$$F_{2d}(x_B, Q^2) = \int_{x_B}^{A} dy\, \mathcal{S}_A(y,\gamma) F_2^{TMC+HT}(x_B/y, Q^2) \left(1 + \frac{\delta^{off} F_2(x)}{F_2(x)}\right)$$

Free nucleon str.fn.

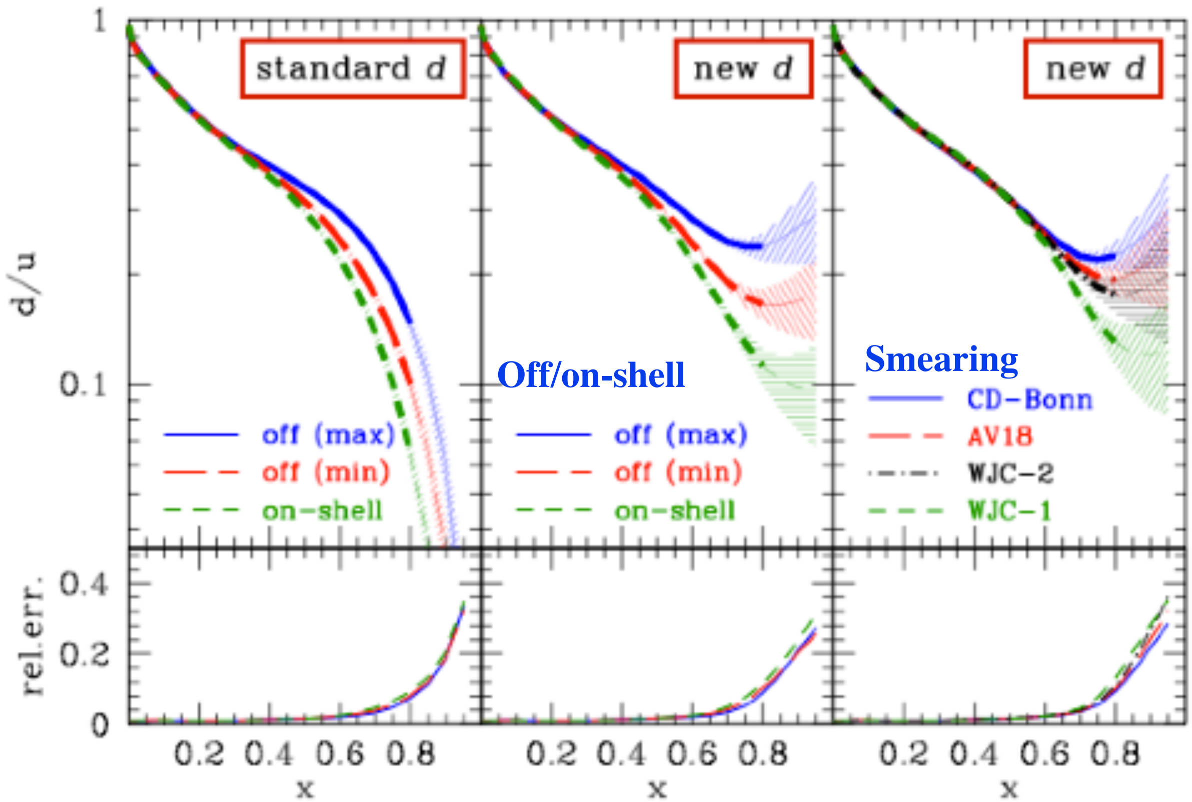
"Smearing function"

Off-shell correction



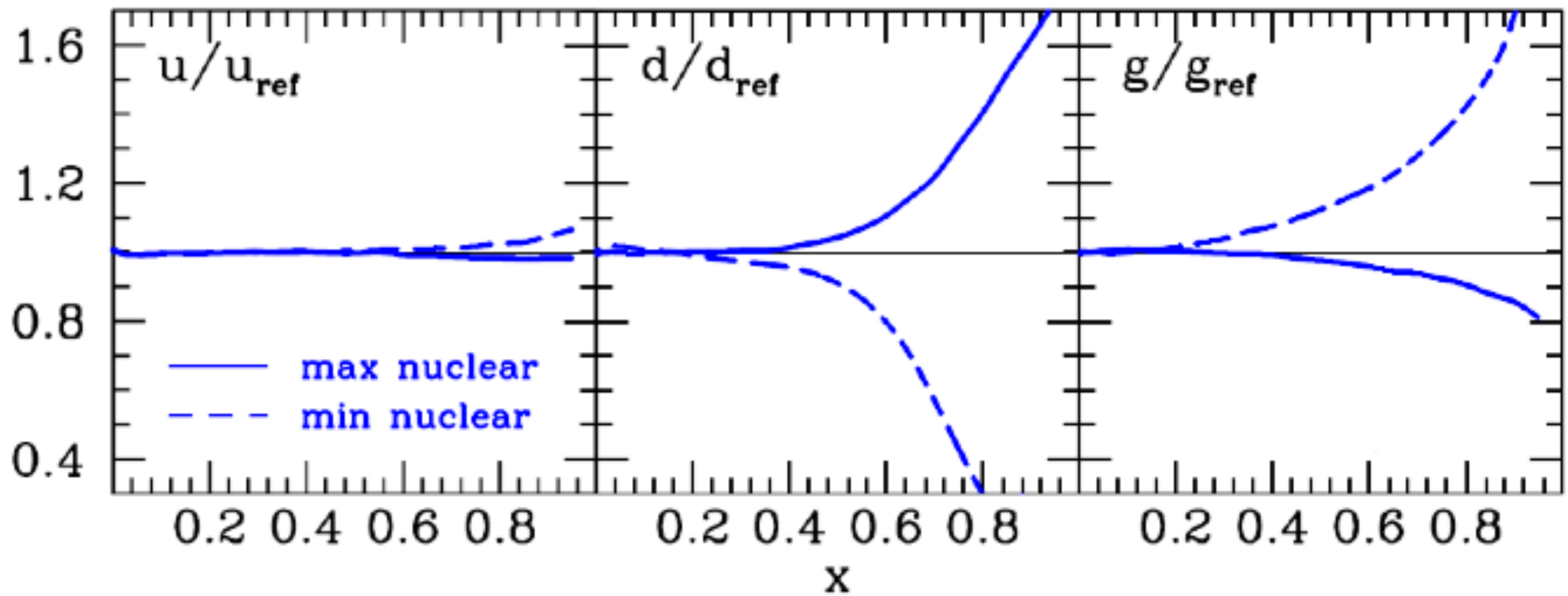


CJ fits: new d-quark results



- Dramatic increase in d PDF in x → 1 limit with more flexible parameterization

Nuclear Model Systematic Errors



Accardi et al. PRD ***84****, 014008 (2011)*

- Large sensitivity to the model for nuclear corrections
  - d-quarks: directly - due to corrections applied to $F_2(d)$
  - gluons: indirectly- due to correlations induced by jet data

Kulagin-Petti Model of Nuclear Effects

hep-ph/0412425

- Global Approach -aiming to obtain quantitative calculations covering the complete range of x and Q^2 available with thorough physics basis for fit to data.
- Different effects on structure functions (SF) are taken into account:

$$F_i^A = F_i^{p/A} + F_i^{n/A} + F_i^{\pi/A} + \delta F_i^{\mathrm{coh}}$$

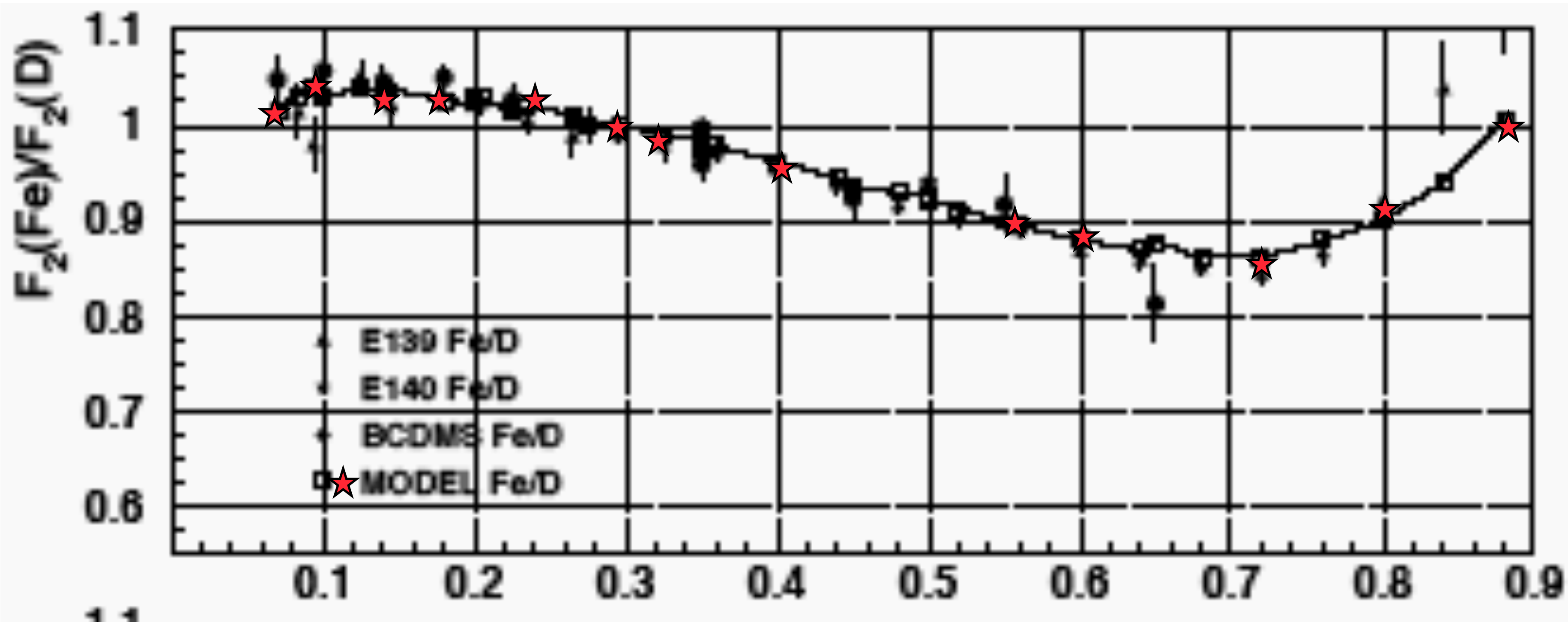
  - $F_i^{p(n)/A}$ bound proton(neutron) SF with Fermi Motion, Binding (FMB) and Off-Shell effect (OS)
  - $F_i^{\pi/A}$ nuclear Pion excess correction (PI)
  - $\delta F_i^{\mathrm{coh}}$ contribution from coherent nuclear interactions: Nuclear Shadowing (NS)

- **Fermi Motion** and **Binding** in nuclear structure functions is calculated from the convolution of nuclear spectral function and (bound) nucleon SFs:
- Since bound nucleons are off-mass shell there appears dependence on the nucleon virtuality $\kappa^2 = (M + \varepsilon)^2 - k^2$ where we have introduced an **off-shell structure function $\delta f_2(x)$**

$$F_2(x, Q^2, k^2) = F_2(x, Q^2)\left(1 + \delta f_2(x)(k^2 - M^2)/M^2\right)$$

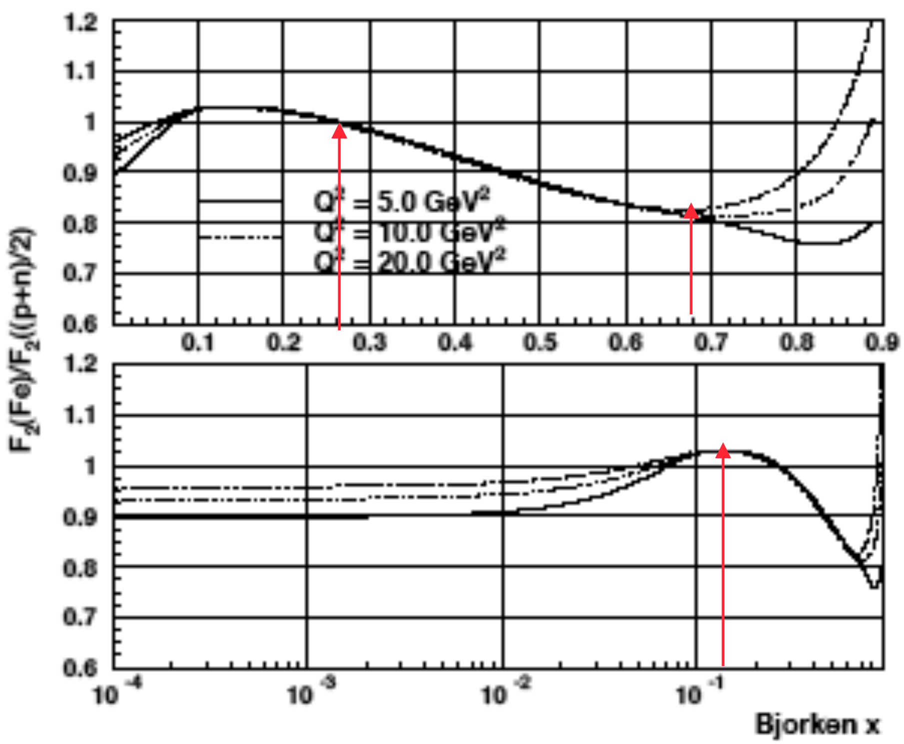
- Leptons can scatter off mesons which mediate interactions among bound nucleons yielding a **nuclear pion correction**

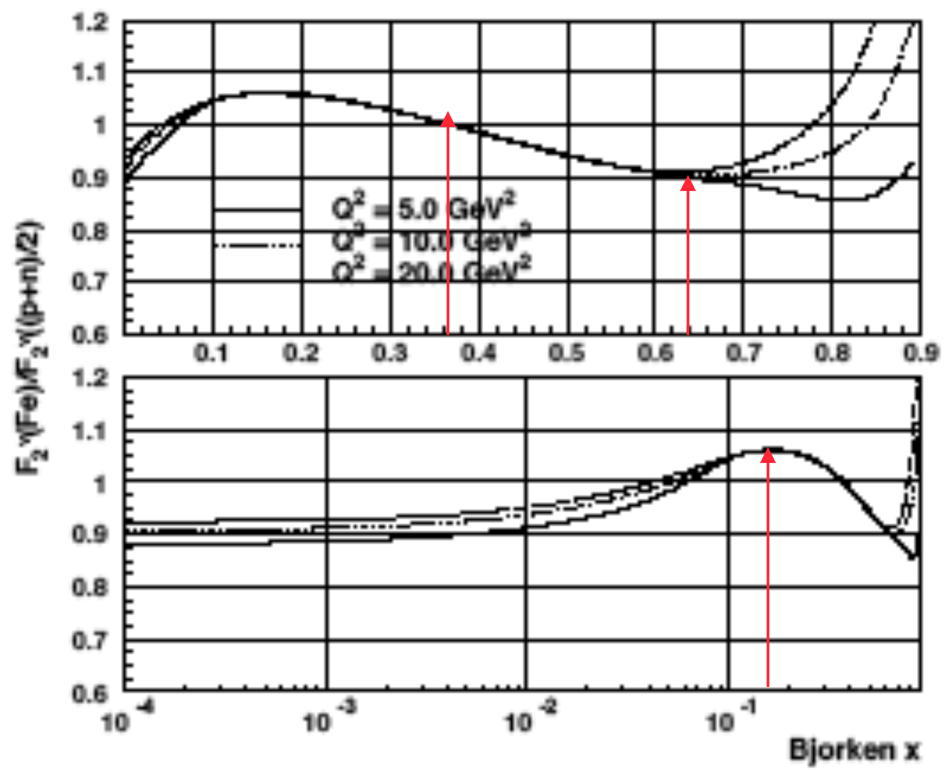
Kulagin-Petti compared to e/μ+Fe data
F_2 (e/μ+Fe) / F_2 (e/μ+D)



Charged Lepton

F_2 (μ+Fe) / F_2 (μ+N) compared to F_2 (ν+Fe) / F_2 (ν+N)



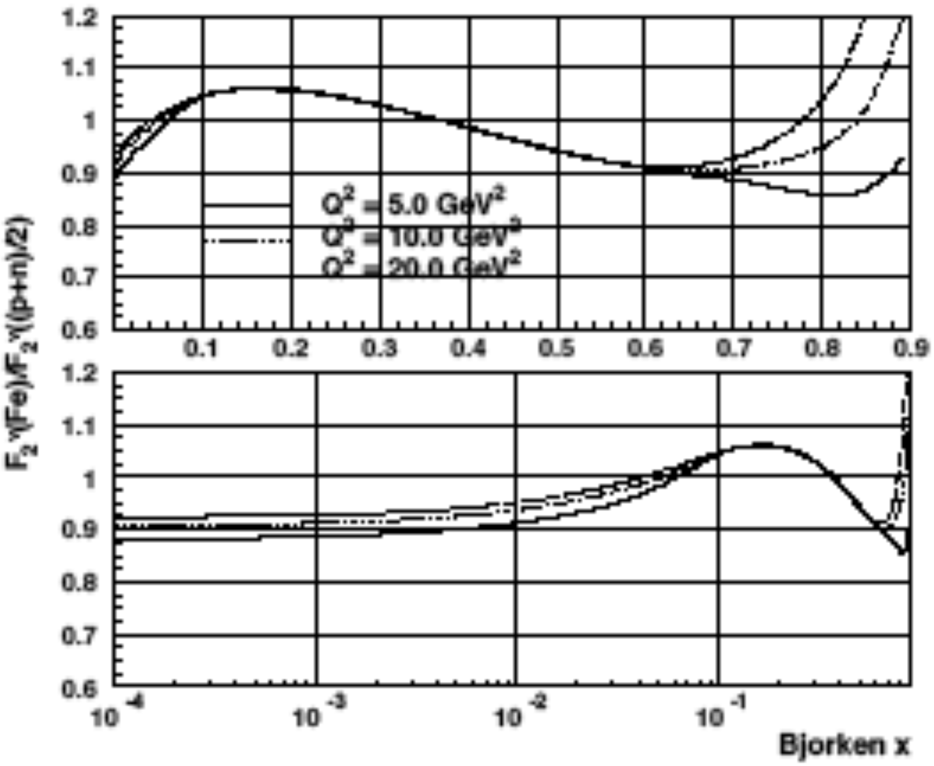


Charged Lepton

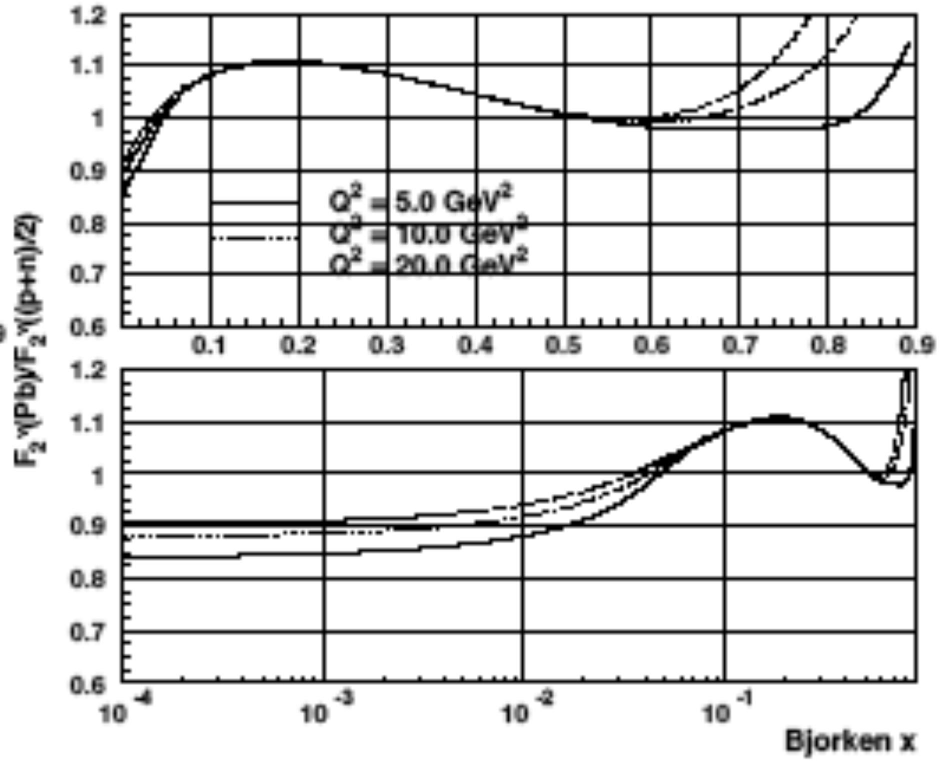
Neutrino

$F_2\,(\nu{+}A)\;/\;F_2\,(\nu{+}N)$

(n excess included in effect)

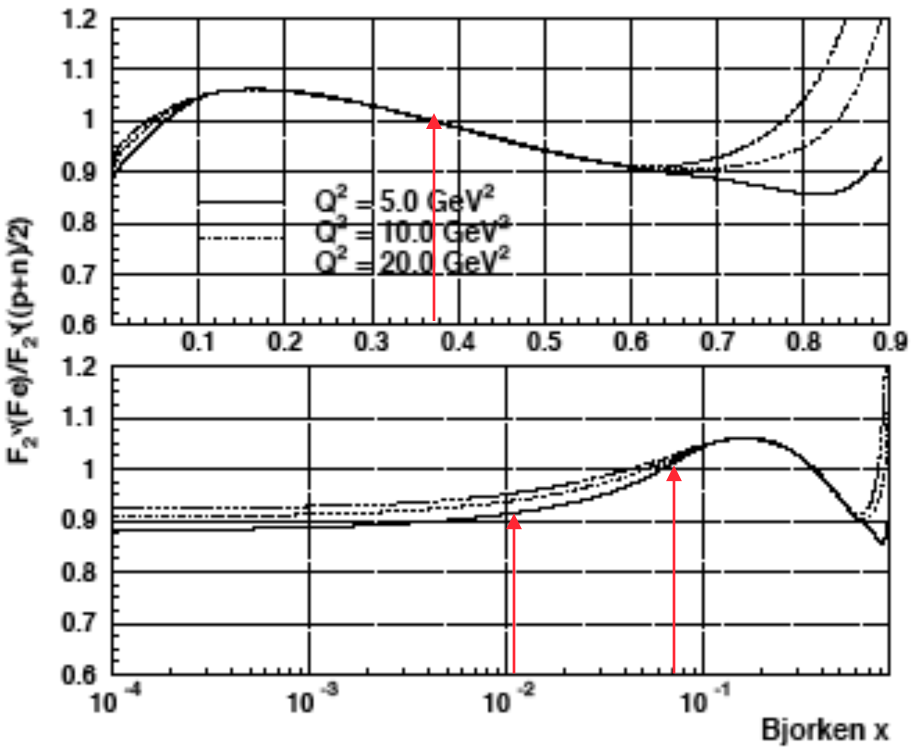


Fe

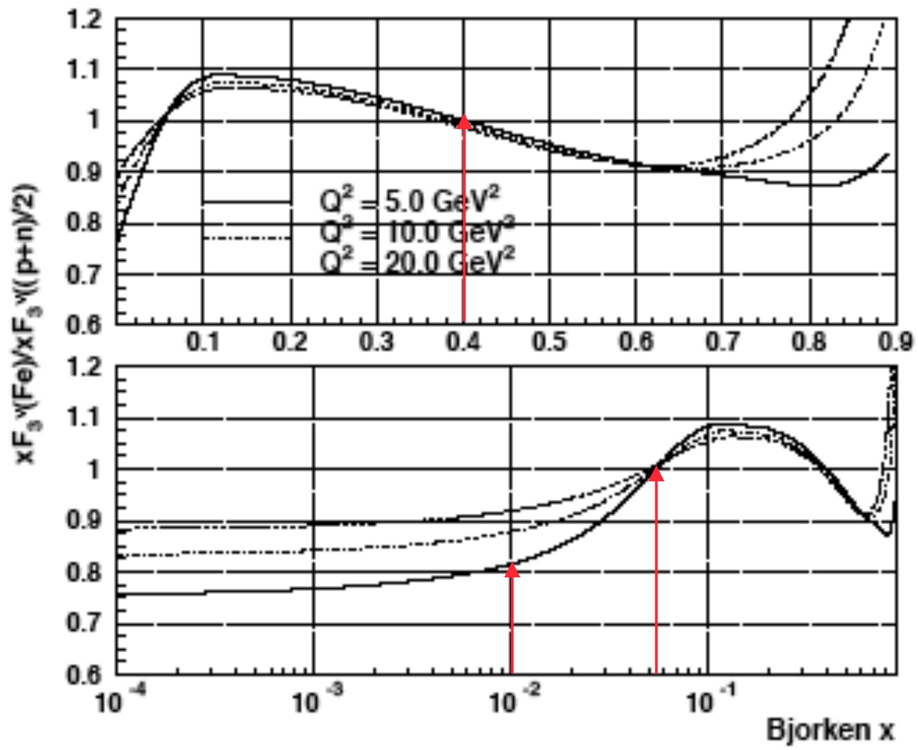


Pb

Kulagin-Petti: ν-Fe Nuclear Effects

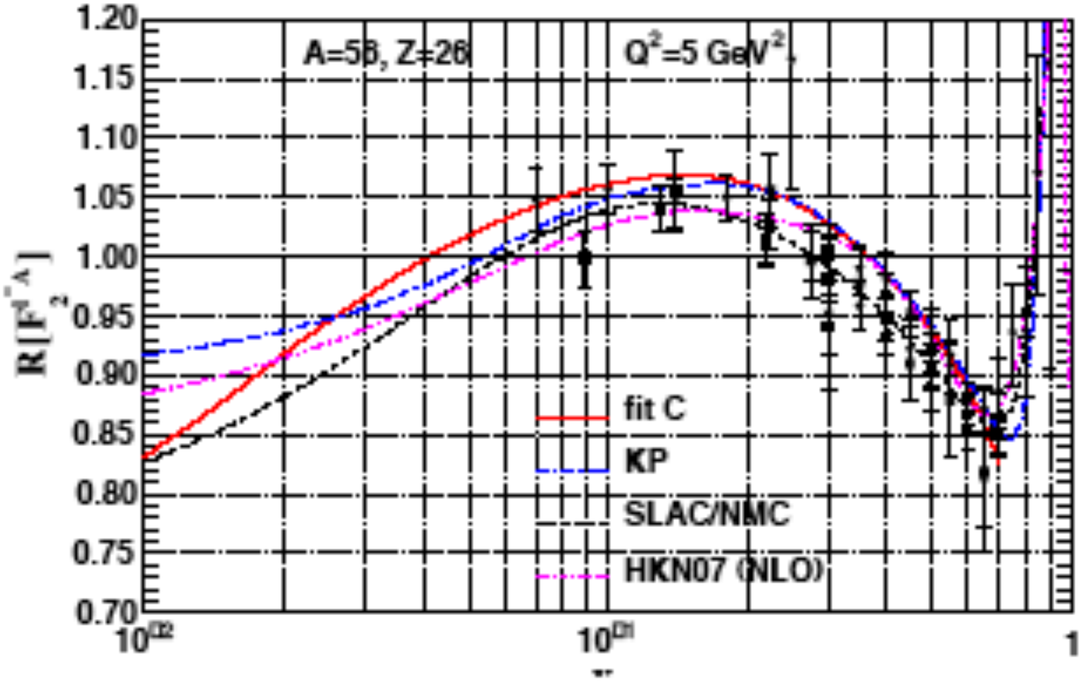


F_2



xF_3

Nuclear Structure Function Corrections
$\ell^{\pm}$ (Fe/D_2)



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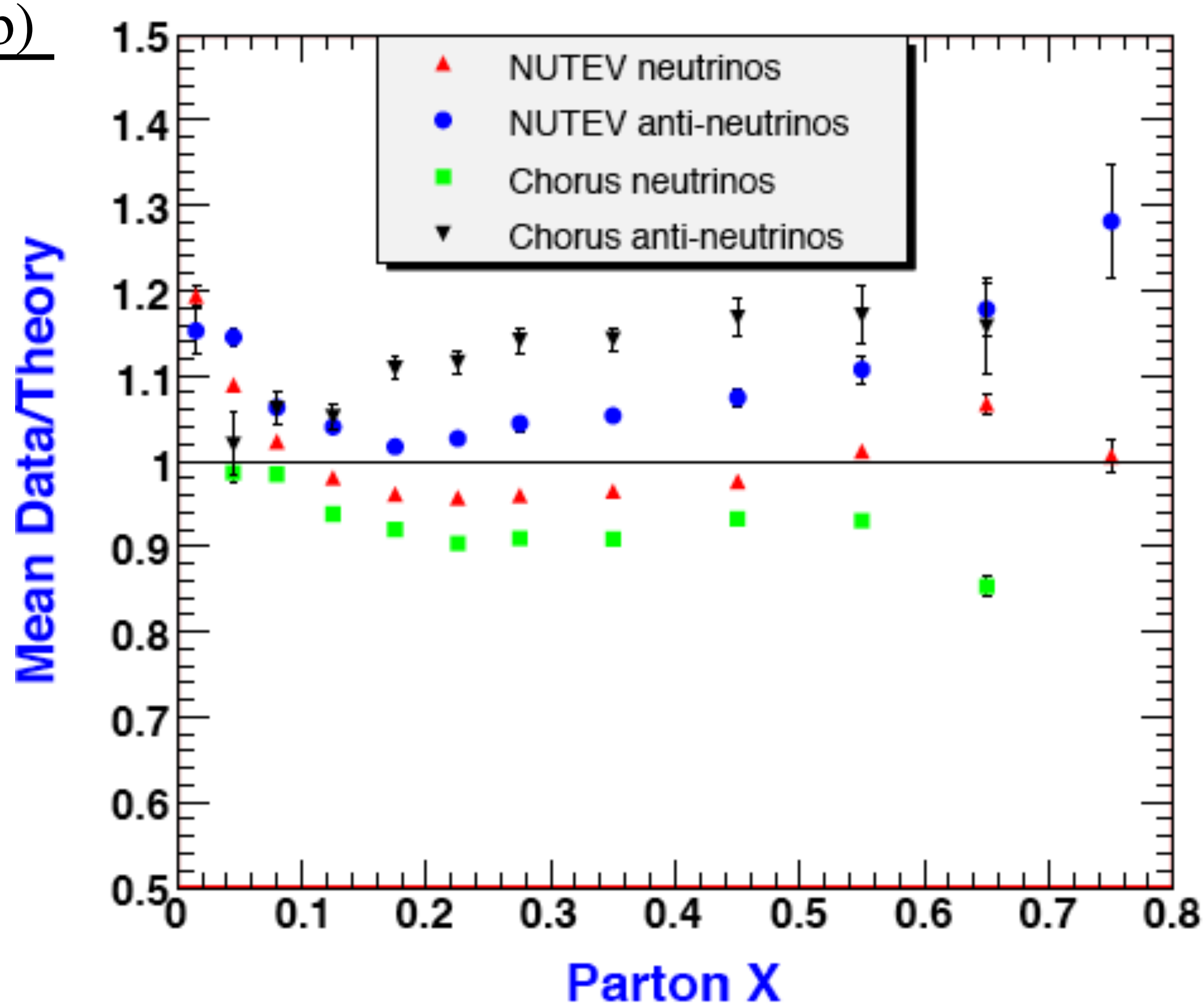
- **<u>Good reason to consider nuclear effects are DIFFERENT in ν - A</u>**.
  - **Presence of axial-vector current.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**

NuTeV σ(Fe) & CHORUS σ(Pb) ν scattering (un-shifted) results compared to reference fit

Kulagin-Petti nuclear corrections

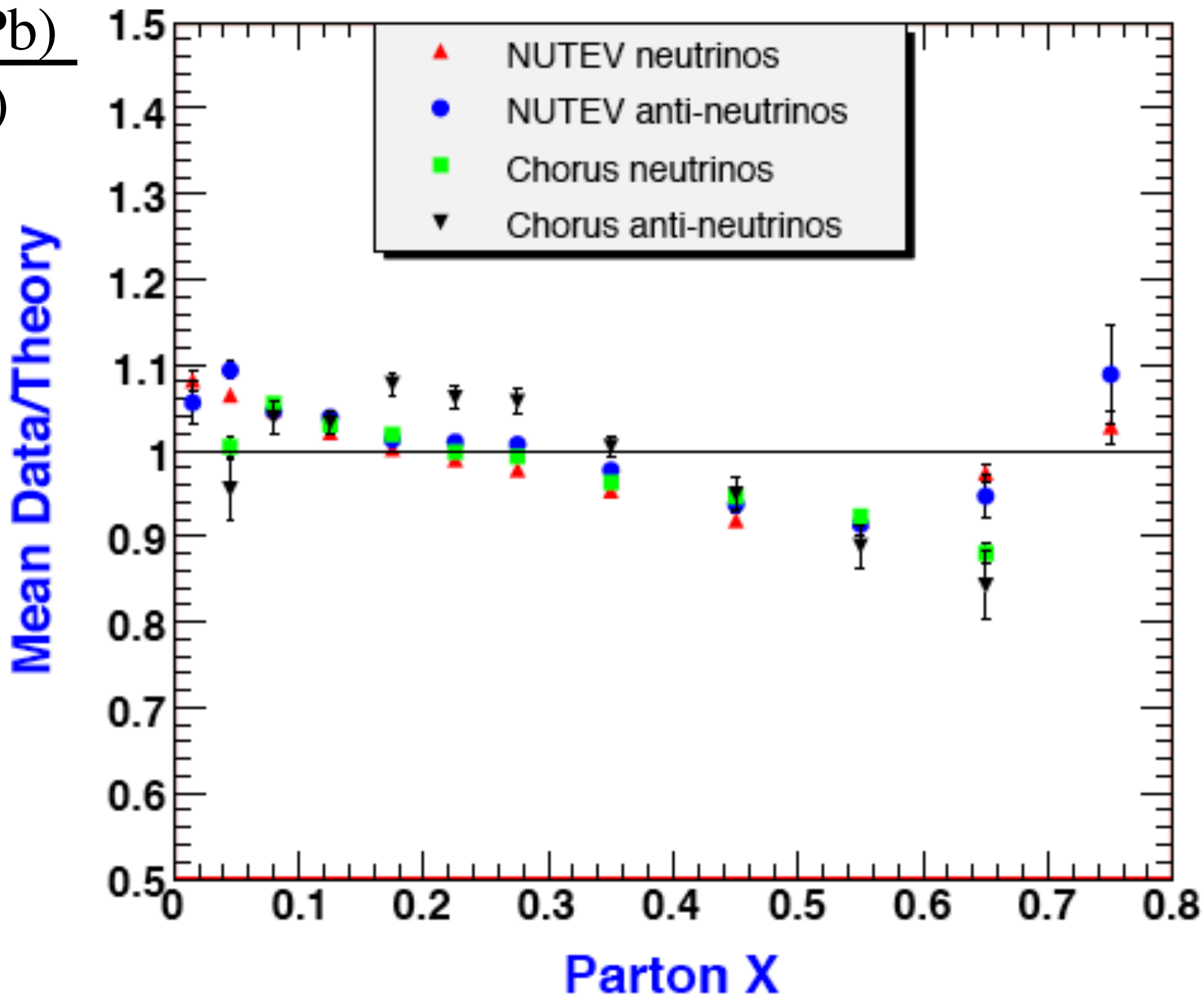
$$\frac{\sigma(\text{Fe or Pb})}{\sigma(n+p)}$$



NuTeV(Fe) and CHORUS (Pb) ν scattering (unshifted) σ results compared to reference fit

no nuclear corrections

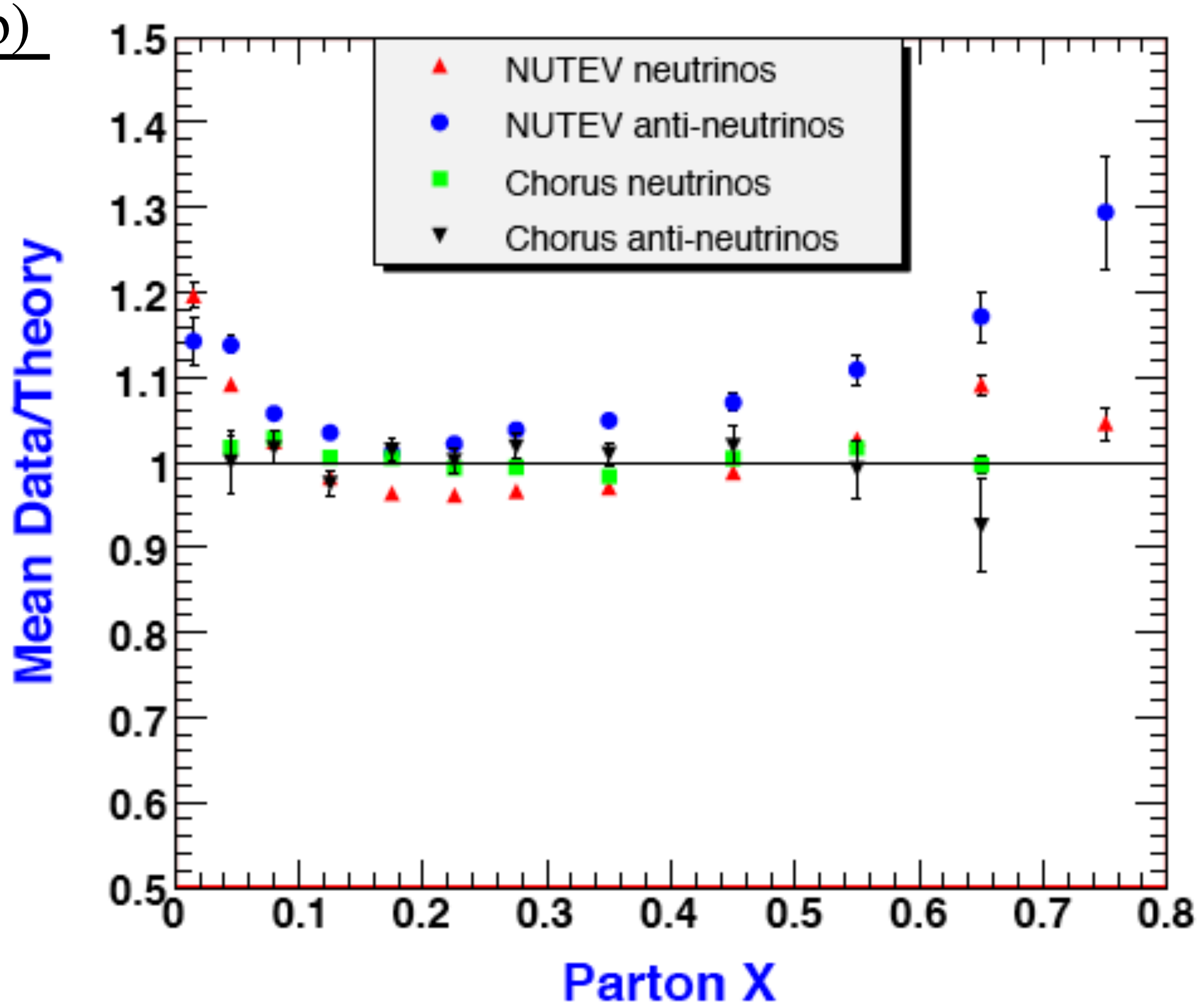
$$\frac{\sigma(\nu\text{Fe or } \nu\text{Pb})}{\sigma(\nu\text{"n+p"})}$$



NuTeV σ(Fe) & CHORUS σ(Pb) ν scattering (shifted) results compared to reference fit

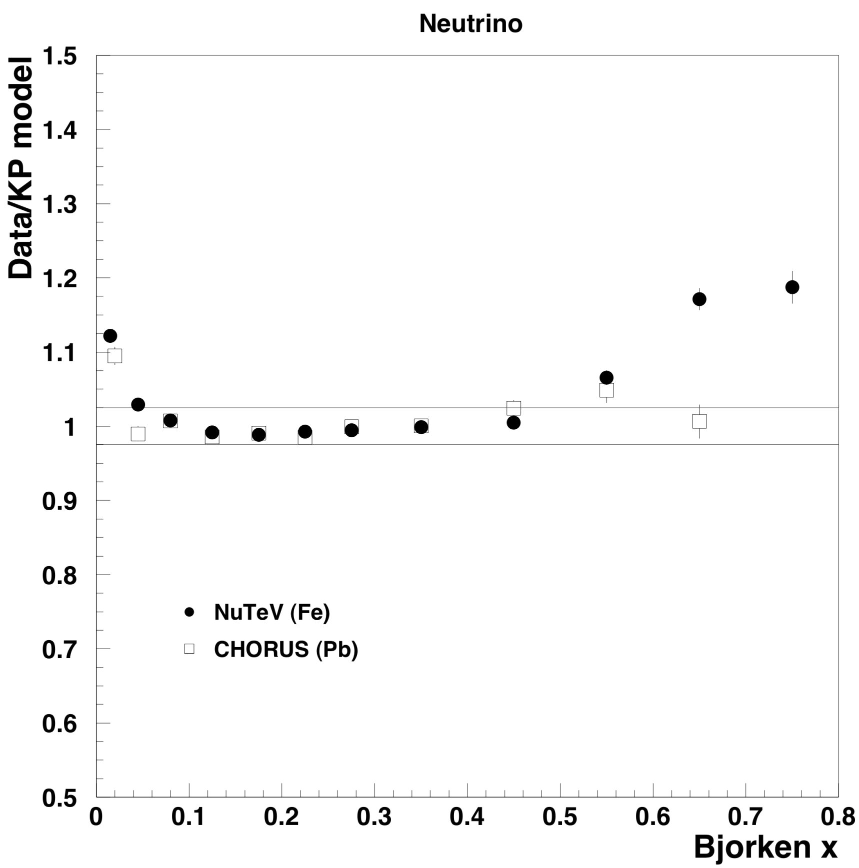
Kulagin-Petti nuclear corrections

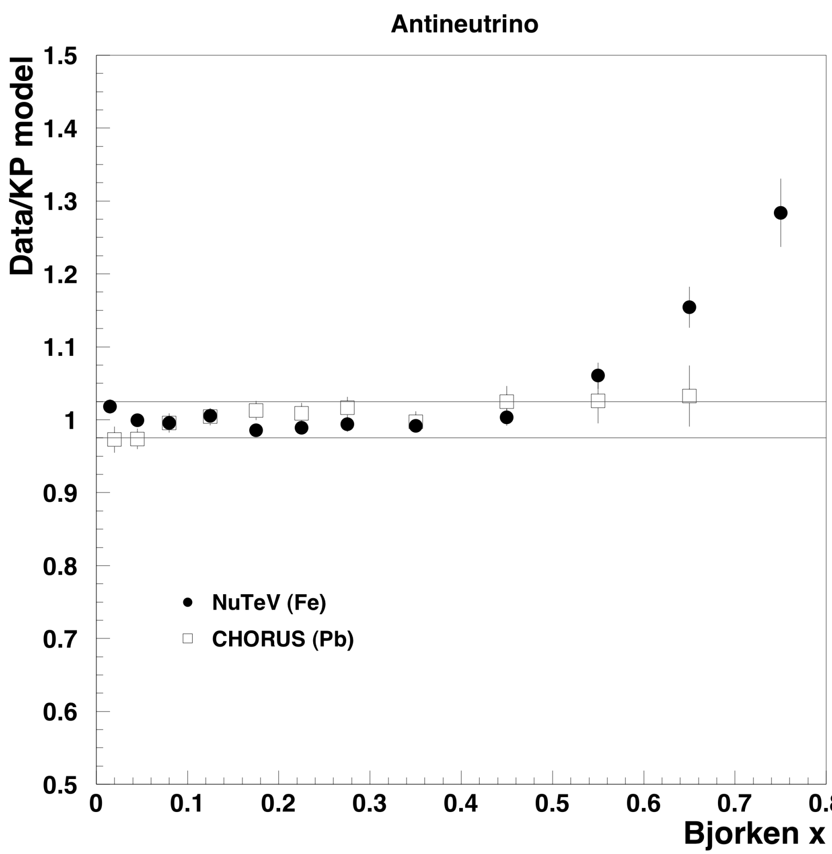
$$\frac{\sigma(\text{Fe or Pb})}{\sigma(n+p)}$$



Comparison of Data to the Kulagin-Petti Model

thanks to Roberto Petti





Extraction of Nuclear PDFs and Nuclear Correction Factors from ν–A Scattering

- PDF Parameterized at Q_0 = 1.3 GeV as

$$xf_i(x,Q_0) = \begin{cases} A_0 x^{A_1}(1-x)^{A_2} e^{A_3 x}(1+e^{A_4}x)^{A_5} & : i = u_v, d_v, g, \bar{u}+\bar{d}, s, \bar{s}\,, \\ A_0 x^{A_1}(1-x)^{A_2} + (1+A_3 x)(1-x)^{A_4} & : i = \bar{d}/\bar{u}\,, \end{cases}$$

- PDFs for a nucleus are constructed as:

$$f_i^A(x,Q) = \frac{Z}{A}\, f_i^{p/A}(x,Q) + \frac{(A-Z)}{A}\, f_i^{n/A}(x,Q)$$

- Resulting in nuclear structure functions:

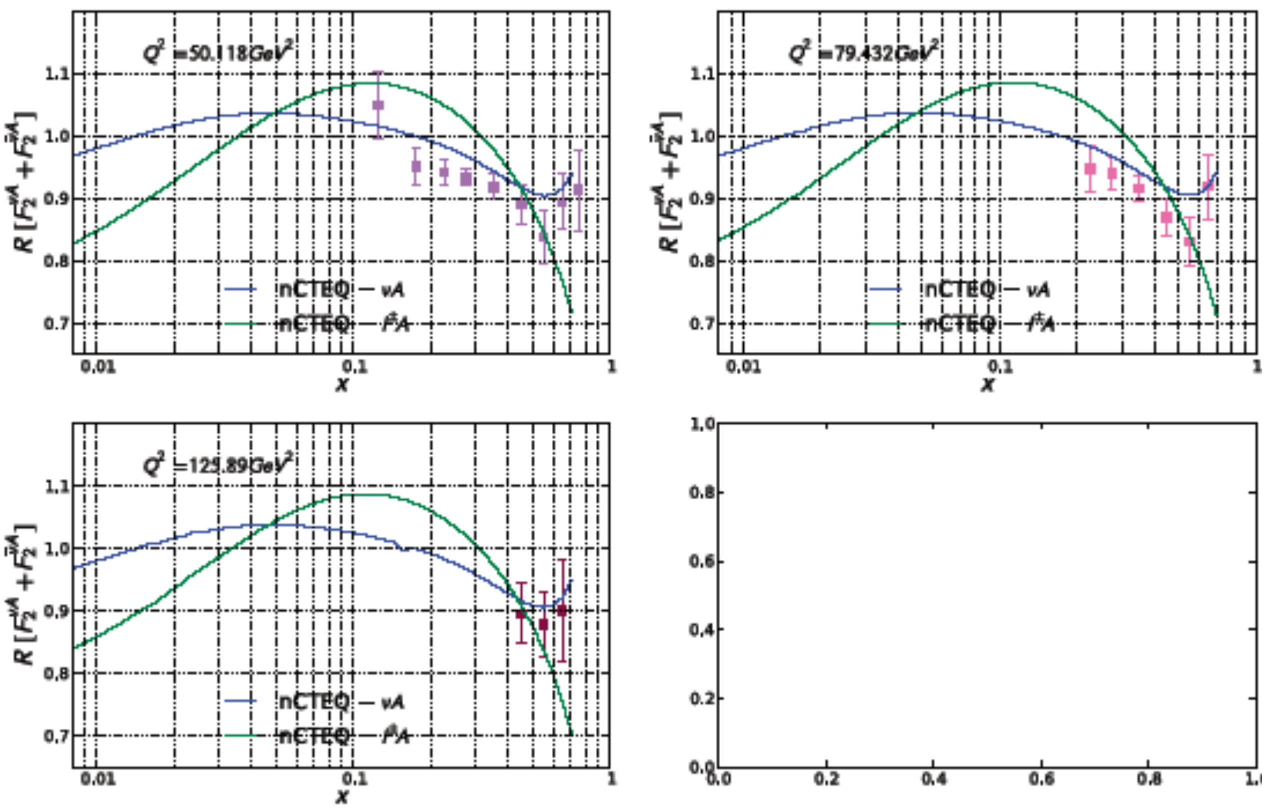
$$F_i^A(x,Q) = \frac{Z}{A}\, F_i^{p/A}(x,Q) + \frac{(A-Z)}{A}\, F_i^{n/A}(x,Q)$$

- The differential cross sections for CC scattering off a nucleus::

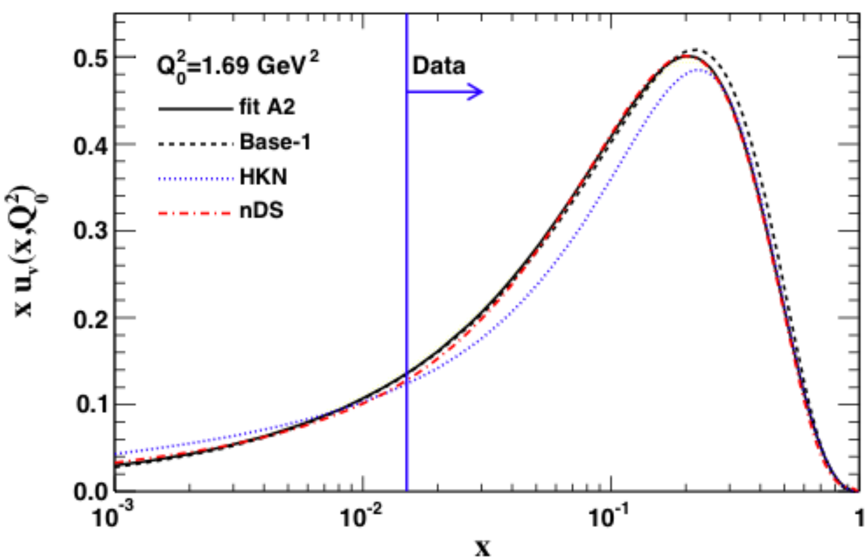
$$\frac{d^2\sigma}{dx\,dy}^{\overset{(-)}{\nu}A} = \frac{G^2 M E}{\pi}\Big[(1-y-\frac{Mxy}{2E})F_2^{\overset{(-)}{\nu}A} + \frac{y^2}{2} 2xF_1^{\overset{(-)}{\nu}A} \pm y(1-\frac{y}{2})xF_3^{\overset{(-)}{\nu}A}\Big]$$

A More-Detailed Look at Differences

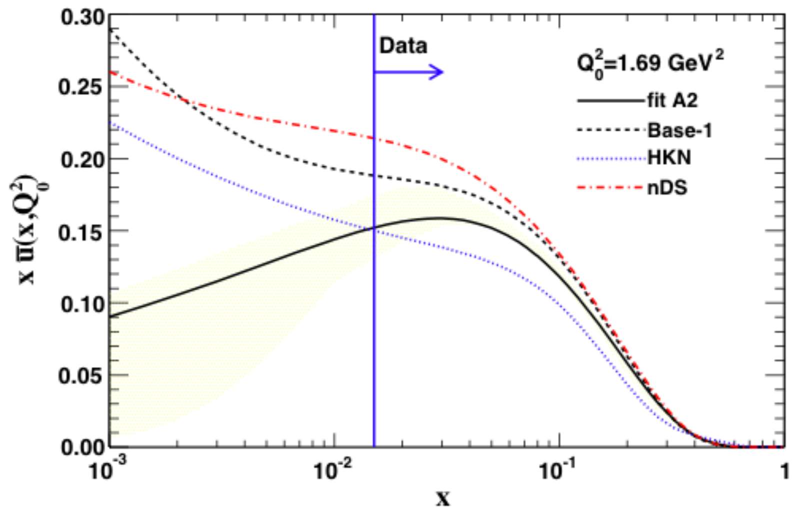
- NLO QCD calculation of $\frac{F_2^{\nu A} + F_2^{\bar{\nu} A}}{2}$ in the ACOT-VFN scheme
  - charge lepton fit undershoots low-x data & overshoots mid-x data
  - low-Q^2 and low-x data cause tension with the shadowing observed in charged lepton data



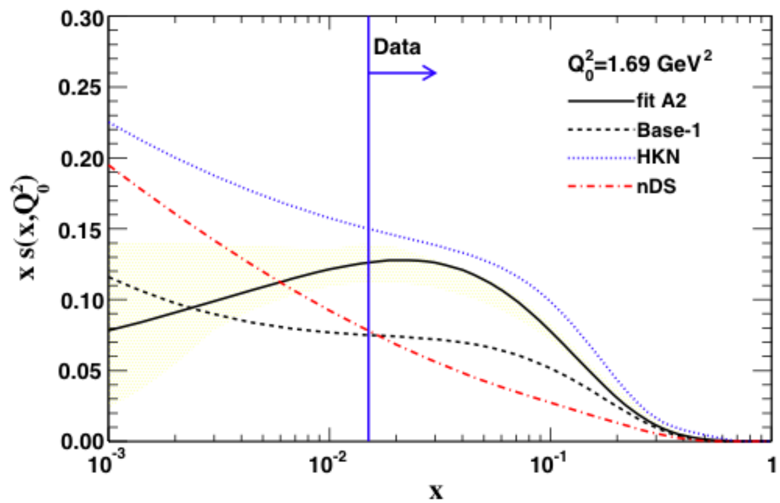
Iron PDFs



Q$_0^2$=1.69 GeV^2
fit A2
Base-1
HKN
nDS
Data
x u$_v$(x,Q$_0^2$)
x



Data
Q$_0^2$=1.69 GeV^2
fit A2
Base-1
HKN
nDS
x $\bar{u}$(x,Q$_0^2$)
x



Data
Q$_0^2$=1.69 GeV^2
fit A2
Base-1
HKN
nDS
x s(x,Q$_0^2$)
x

If Difference between both $\ell^{\pm}$-A and ν–A persists?

- Another idea also from Guzey and colleagues is the observation that (in leading order):

$$\frac{d\sigma^{\nu A}}{dxdy} = \frac{G_F^2 M_W^4}{(Q^2+M_W^2)^2}\frac{ME}{\pi}2x\left[d^A + s^A + (1-y)^2(\bar{u}^A + \bar{c}^A)\right]$$
$$\frac{d\sigma^{\bar{\nu} A}}{dxdy} = \frac{G_F^2 M_W^4}{(Q^2+M_W^2)^2}\frac{ME}{\pi}2x\left[\bar{d}^A + \bar{s}^A + (1-y)^2(u^A + c^A)\right]$$

  - In the shadowing region at low-x, y is large and the σ_ν are primarily probing the d- and s-quarks.
- This is very different from $l^{\pm}$ scattering where the d- and s-quarks are reduced by a factor of 4 compared to the u- and c-quarks.
  - If shadowing of the d- or s-quarks is negligible this would explain the NuTeV result.
  - Diminished shadowing of the nuclear s-quark is suggested by early extraction of nPDFs by nCTEQ.